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Blend Down Monitoring System Fissile Mass Flow Monitor Implementation at the ElectroChemical Plant, Zelenogorsk, Russia

November 2005

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Nuclear Science and Technology Division

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ABBREVIATED TERMS

BDMS	Blend Down Monitoring System
BGO	bismuth germanium oxide
DIEC	detector interface electronics card
DOE	U.S. Department of Energy
ECP	Electro Chemical Plant (Zelenogorsk)
EM	Enrichment Monitor
FMFM	Fissile Mass Flow Monitor
HEU	highly enriched uranium
LEU	low enriched uranium
MINATOM	Ministry for Atomic Energy of the Russian Federation
ORNL	Oak Ridge National Laboratory
P-LEU	product low enriched uranium
PMT	photomultiplier tube
SM	source modulator
UEIP	Ural Electrochemical Integrated Plant (Novouralsk)

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ABSTRACT

The implementation plans and preparations for installation of the Fissile Mass Flow Monitor (FMFM) equipment at the ElectroChemical Plant (ECP), Zelenogorsk, Russia, are presented in this report. The FMFM, developed at Oak Ridge National Laboratory, is part of the Blend Down Monitoring System (BDMS), developed for the U.S. Department of Energy Highly Enriched Uranium (HEU) Transparency Implementation Program. The BDMS provides confidence to the United States that the Russian nuclear facilities supplying the lower-assay (~4%) product low enriched uranium (P-LEU) to the United States from down-blended weapons-grade HEU are meeting the nonproliferation goals of the government-to-government HEU Purchase Agreement, signed between the Russian Federation and the United States in 1993. The first BDMS has been operational at Ural Electrochemical Integrated Plant, Novouralsk, since February 1999 and is successfully providing HEU transparency data to the United States. The second BDMS was installed at ECP in February 2003. The FMFM makes use of a set of thermalized californium-252 (^{252}Cf) spontaneous neutron sources for a modulated fission activation of the UF_6 gas stream for measuring the ^{235}U fissile mass flow rate. To do this, the FMFM measures the transport time of the fission fragments created from the fission activation process under the modulated source to the downstream detectors by detecting the delayed gamma rays from the fission fragments. The FMFM provides unattended, nonintrusive measurements of the ^{235}U mass flow in the HEU, LEU blend stock, and P-LEU process legs. The FMFM also provides the traceability of the HEU flow to the product process leg. This report documents the technical installation requirements and the expected operational characteristics of the ECP FMFM.

1. INTRODUCTION

The Highly Enriched Uranium (HEU) Transparency Agreement between the United States and the Russian Federation requires implementation of transparency measures in the Russian facilities that are supplying the lower-assay product low enriched uranium (P-LEU) to the United States from down-blended weapon-grade HEU material. Moreover, the agreement provides for the monitoring of the down-blending of HEU at an assay of ~90% with blend stock LEU at an assay of ~1.5% to produce P-LEU at an assay of ~4% (reactor-grade material), to be used in U.S. nuclear power plants. The Ministry for Atomic Energy of the Russian Federation (MINATOM) and the U.S. Department of Energy (DOE) have agreed on implementing transparency measures at the Ural Electrochemical Integrated Plant (UEIP), at Novouralsk, Russia, and at the Electro Chemical Plant (ECP), at Zelenogorsk, Russia.

The transparency measures include the installation of the Blend Down Monitoring System (BDMS) to monitor the enrichment and fissile mass flow of the HEU blending processes at UEIP and at ECP. The BDMS has been developed to provide unattended and continuous monitoring of the blending operations at the Russian facilities. The BDMS consists of the Fissile Mass Flow Monitor (FMFM), which was developed at Oak Ridge National Laboratory (ORNL) [1], and the Enrichment Monitor (EM), which was developed at Los Alamos National Laboratory [2]. The FMFM provides unattended measurements of ^{235}U mass flow of the uranium hexafluoride (UF_6) gas in the process legs that carry the HEU, the LEU blend stock, and the resulting lower-assay P-LEU. The FMFM also traces fission products generated in the HEU flow through the blending operation into the P-LEU flow, thus confirming that the HEU material is down-blended (Fig. 1).

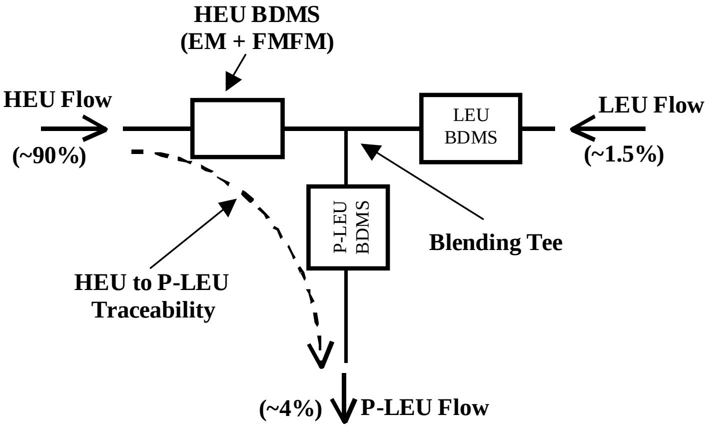

Fig. 1. The BDMS installed on an HEU blending tee.

Traceability of HEU material gives the United States significant confidence that the HEU is indeed being blended into a lower-assay material. The first BDMS was successfully implemented at the UEIP and has been operational since February 1999. As part of the Transparency Implementation Program, DOE is continuing to implement FMFM instrumentation for the rest of the Russian nuclear facilities that are supplying the down-blended HEU material for the purchase agreement. The primary topic of this report is the FMFM implementation at the ECP HEU blending facility.

2. FMFM OPERATIONAL DESCRIPTION

2.1 FISSILE MASS FLOW MEASUREMENTS

As shown in Fig. 1, the FMFM measures the fissile mass flow of the UF_6 gas in the HEU, the P-LEU, and the LEU blend stock process legs of the blending tee. The main measurement principle for the FMFM relies on the production of fission fragments that are carried by the UF_6 flow and that emit delayed gamma rays. To produce the fission fragments, thermalized neutrons (neutrons emitted by ^{252}Cf sources placed in an annular sleeve filled with moderator material that surrounds the pipe) are modulated by a neutron-absorbent shutter to induce fission in the UF_6 (Fig. 2).

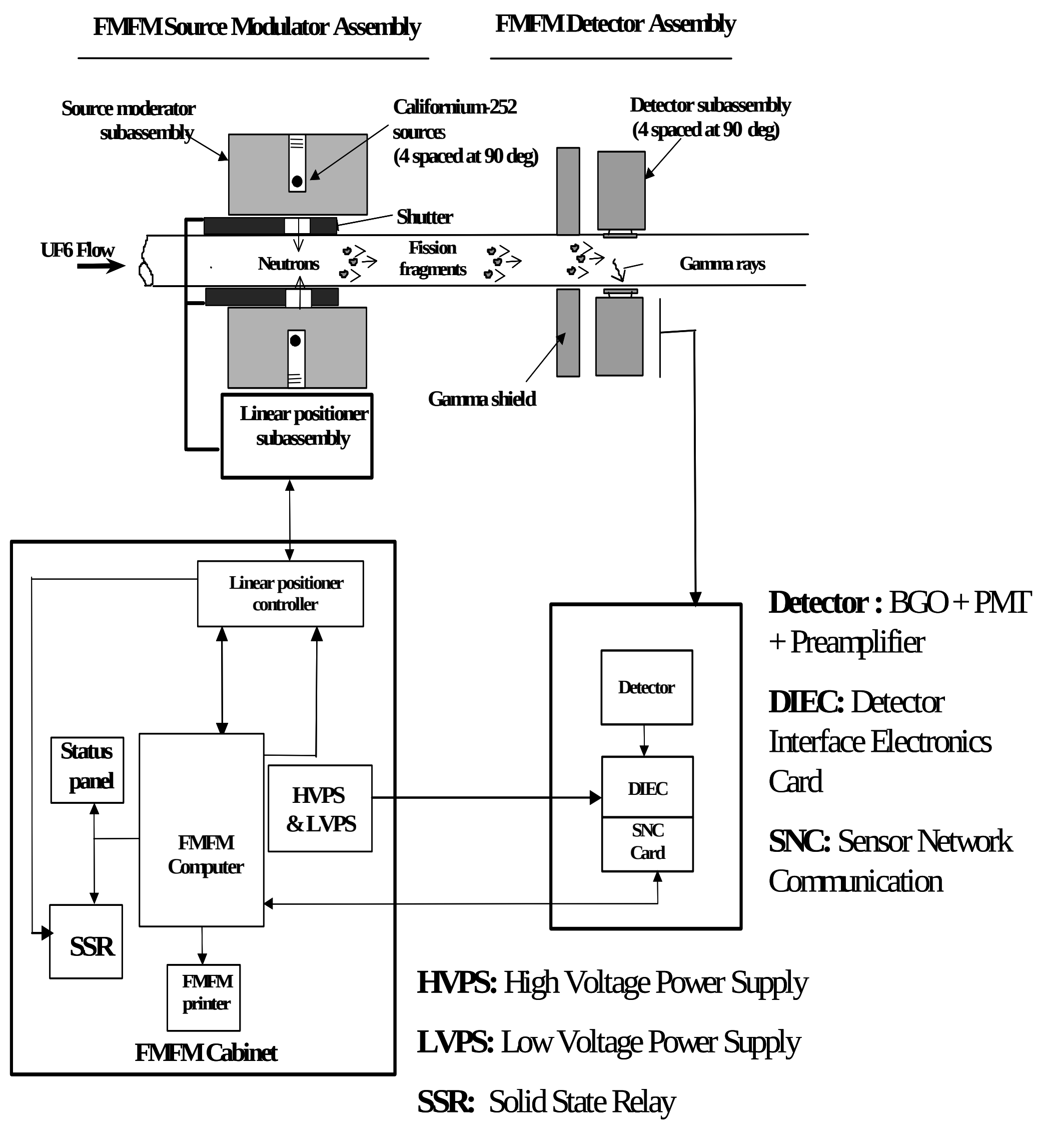

Fig. 2. The FMFM operational principle and major components. The source moderator is covered with lead and lithiated polyethylene shielding to achieve the facility dose rate requirement (0.3 mrem/h at 1 m).

The induced fissions are time-modulated by using a neutron-absorbing shutter to create a time signature in the UF_6 gas flow. A gamma ray measuring detector (see Fig. 2), located downstream of the source modulator (SM), measures delayed gamma rays emitted by the resulting fission fragments. Then, the FMFM determines the fissile mass flow rate from two independent measurements: (1) the observed delay in the time-correlated measurement between the SM and the detector signal provides the velocity of UF_6, and (2) its amplitude is related to the ^{235}U concentration in UF_6 (see Fig. 3).

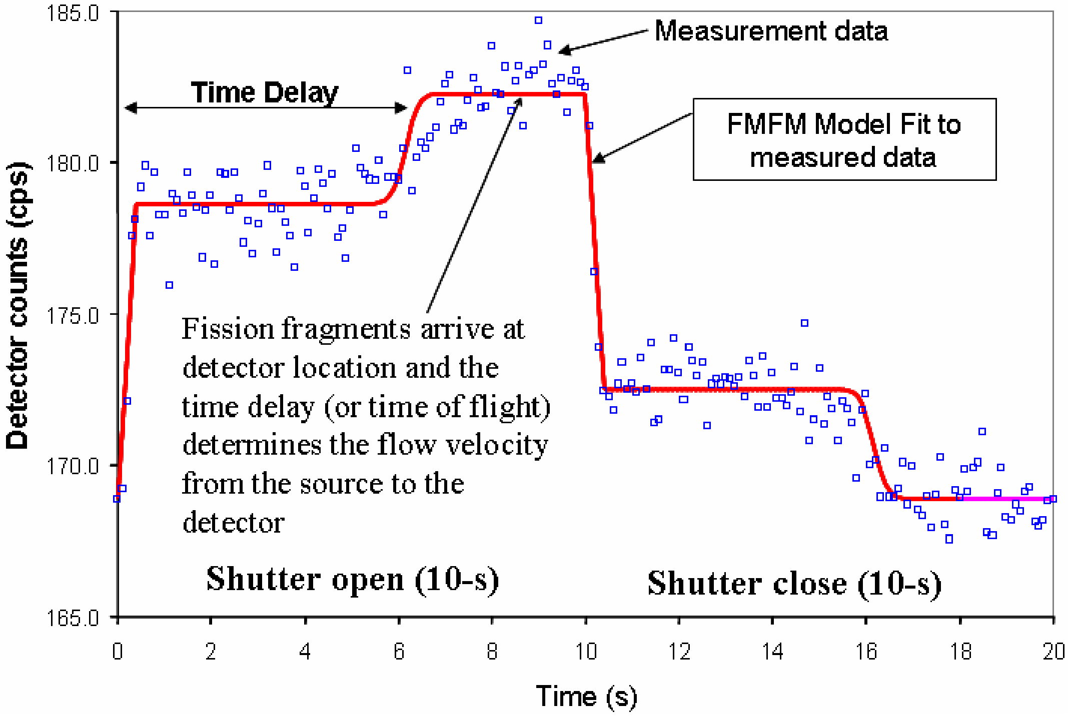

Fig. 3. The FMFM-measured detector signal waveform and the detector counts are collected every 100 ms, as the shutter cycles.

To predict the detector response from the measurements of the gamma rays resulting from the fission fragment production downstream of the source, it is necessary to estimate (1) the fraction of fission fragments that remain in the UF_6 gas following an induced fission by the ^{252}Cf-neutron source, (2) the transport of the fission products in the pipe, and (3) the rate of decay of the fission products produced in the UF_6 gas. The details of the FMFM models employed to predict the detector response are documented in other publications [2, 3, 4].

2.2 HEU TRACEABILITY MEASUREMENTS

The principle of the FMFM HEU traceability measurement is to trace the HEU material through the blending tee by detecting in the P-LEU leg detector delayed gamma rays emitted by fission products generated by the SM in the HEU leg (see Fig. 1). The fission fragments that are created from the ^{252}Cf–induced fissions are relatively long-lived [2]. Thus their delayed gamma rays can be detected at long distances from the source. This technique is used by FMFM to monitor flow continuity from the FMFM SM on the HEU leg to the detector on the P-LEU leg.

The FMFM tracing calculation is based on the difference in total count rate at the P-LEU detector with and without the HEU leg shutter in operation. The FMFM reports the HEU tracing results in terms of confidence level, which is a measure of the probability that the HEU flowed through the blending tee. The time constant for the low-frequency "tagging signal" must be optimized based on the source-detector time delay and on the number of mixing volumes. For the ECP system the FMFM cycles the HEU leg shutter open and closed every 10 s for a 10-min period and then closes it for the next 10-min period, as illustrated in Fig. 4. This operation results in a 20-min cycle of buildup and decay of fission products that allows for continuity monitoring by comparing the difference in the P-LEU leg detector counts with and without induced fissions.

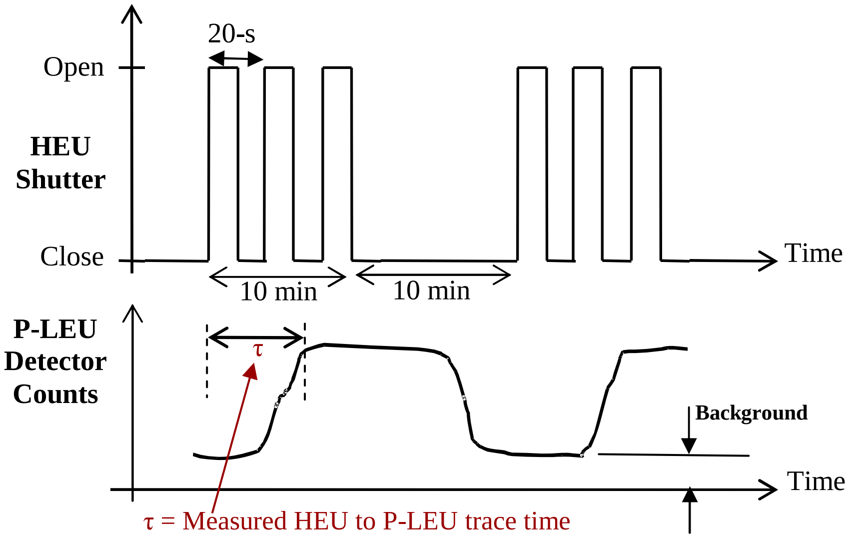

Fig. 4. The FMFM HEU leg shutter motion pattern used to generate the low-frequency modulation required for the tracing of the HEU flow to the P-LEU leg. The traceability measurement is achieved by detecting the fission fragments tagged on the HEU flow stream with the P-LEU leg detector after a time delay, τ.

The periodic disabling the HEU-leg shutter (every other 10 min) affects the shutter-correlated background level at the P-LEU leg detector. Therefore, the FMFM traceability only uses the data when all shutters are closed. An on-line FMFM computer synchronously controls the shutters on all three SMs, processes acquired detector data, and reports results on the flow and trace measurements.

3. MAJOR FMFM COMPONENTS

The FMFM has three major components: the SM assembly, the detector assembly, and the control cabinet. Figure 2 shows a block diagram of all the pipe-mounted FMFM components for a single fissile flow stream. The SM assembly includes the ^{252}Cf sources, a polyethylene moderator, a neutron absorber shutter, and its associated shielding (Figs. 2, 5, and 6). The moderator subassembly, which contains the ^{252}Cf sources in source plugs, is shown in Fig. 5. The moderator is surrounded by lead and polyethylene shielding to minimize the radiation dose (see Figs. 5 and 6). The measured dose rate is less than 0.3 mrem/h at any point 1 m from the SM, and less than 10 mrem/h at any point in contact with the equipment. These dose rates meet all applicable requirements for the ECP facility installation.

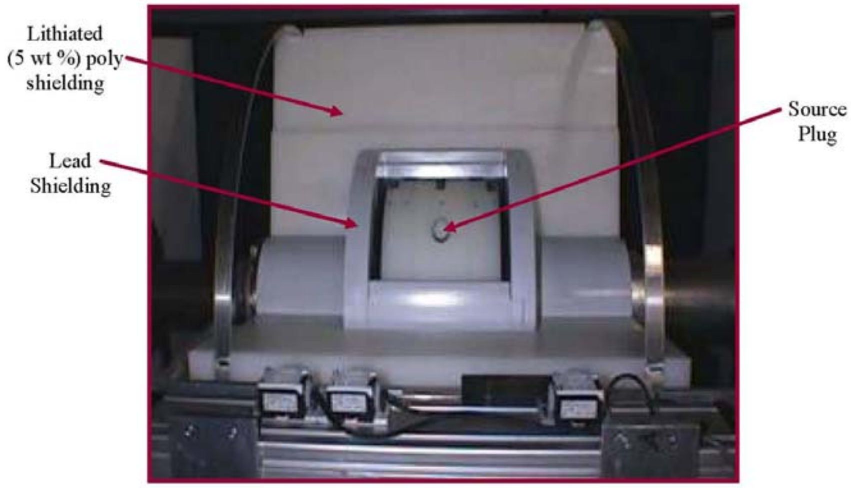

Fig. 5. The FMFM SM. Shown are the lead shielding covering the source moderator, the lithiated (5 weight %) polyethylene shielding placed around the lead, and the shutter positioner.

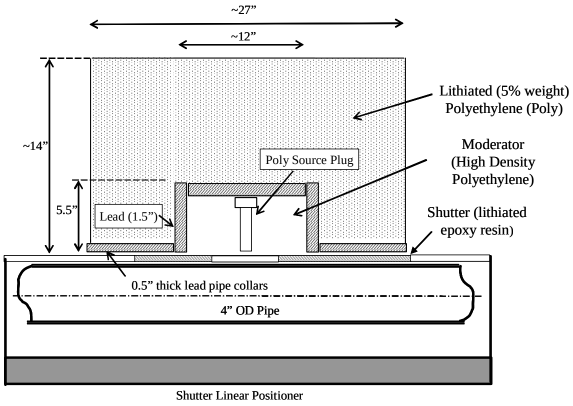

Fig. 6. Details of the FMFM SM assembly and components. Maximum allowable dose rates: 1 mrem/h on surface and < 0.3 mrem/h at 1 m.

The detector assembly is composed of four bismuth germinate oxide (BGO) detectors that surround the pipe. The detector crystals and the photomultiplier tubes (PMTs) are surrounded by lead shielding to minimize room-background effects (see Figs. 2 and 7). In addition, a 3-in. circular gamma shield placed upstream minimizes the radiation background induced by the ^{252}Cf source (see Fig. 7). Each detector subassembly is fitted with a detector interface electronics card (DIEC), as shown in Figs. 2 and 7, which contains the signal-conditioning and discrimination amplifiers. The interface card also includes an on-board computer, which controls its operation and collects detector counts that are periodically downloaded to the main computer in the cabinet for processing.

Fig. 7. The FMFM detector assembly showing the DIEC and the gamma shield.

The pipe-mounted SM and detector assembly shown in Fig. 8 represents a typical HEU leg configuration. The control cabinet provides power conditioning and distribution, control, and data acquisition and processing. Figure 9 shows the BDMS main cabinet installed at ECP. The FMFM cabinet section is on the left; the EM cabinet section is on the right. The details of the FMFM cabinet and its components are shown in Fig. 10.

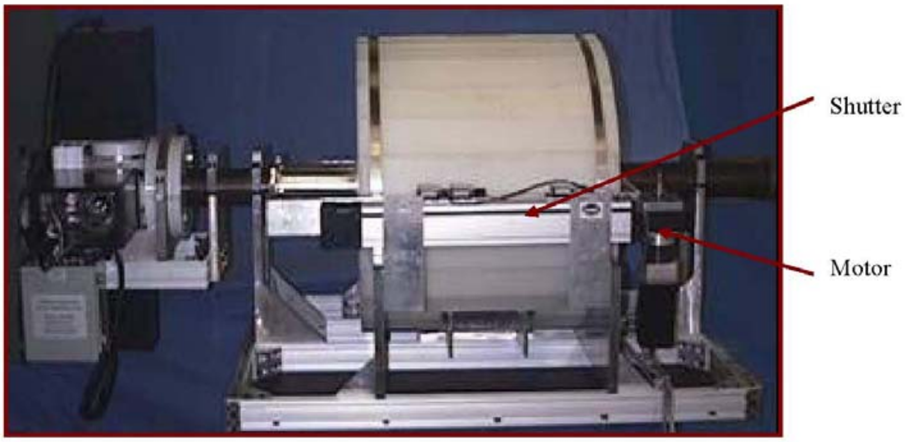

Fig. 8. The FMFM SM assembly with the shutter positioner together with its motor and the detector assembly.

Fig. 9. The BDMS main cabinet housing the FMFM (left) and EM (right) cabinet sections.

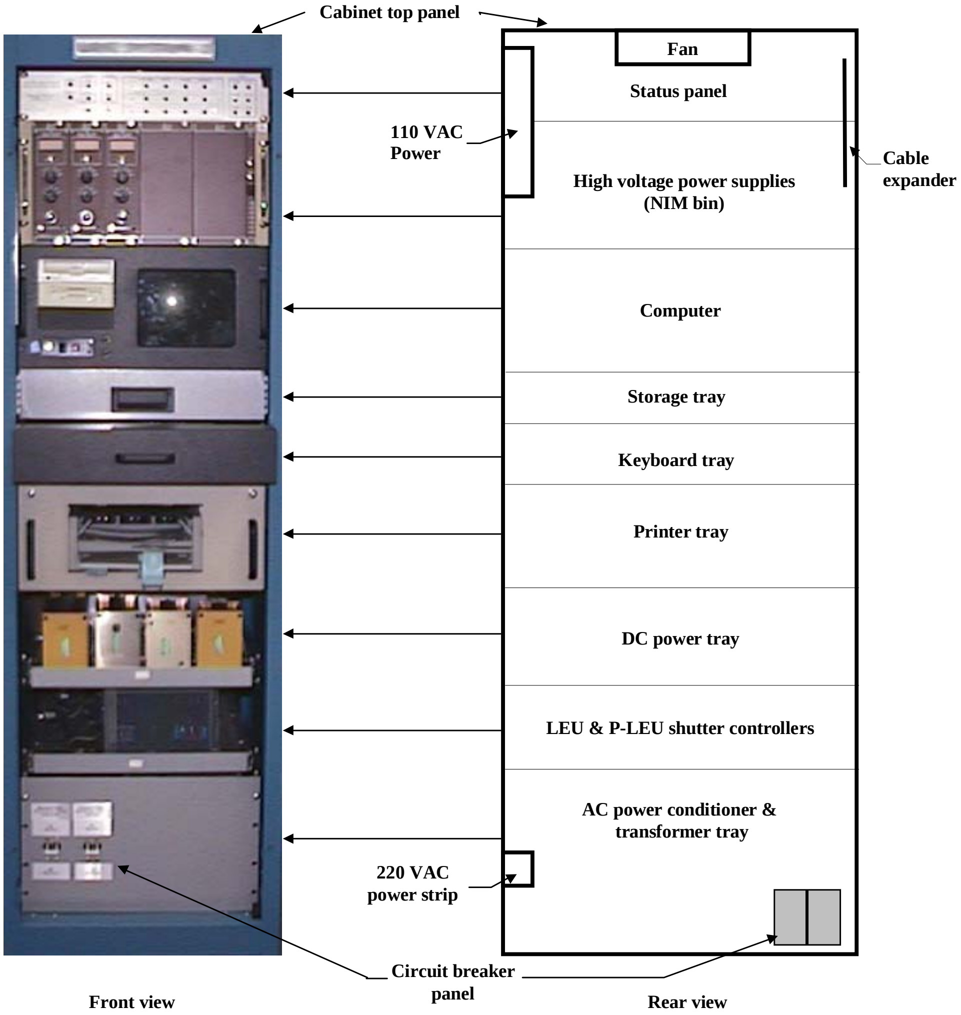

Fig. 10. FMFM cabinet section and components.

4. FMFM IMPLEMENTATION SPECIFICATIONS AT ECP

The block diagram of the BDMS equipment installation layout on the HEU blending system at ECP is shown in Fig. 11; a typical BDMS representing for one leg of HEU blending tee is shown in Fig. 12. The blending system process pipes directly support the FMFM equipment. The process pipes where the BDMS is installed are about 1.25 m off the floor in order to have an easy access to the equipment for maintenance. The major FMFM assembly dimensions and approximate weights are given in Table 1.

An enclosure surrounds the BDMS equipment to control access to the area for the health and safety considerations. The facility radiation dose rate requirement (< 0.3 mrem/h at 1 m from the surface of the equipment housing the ^{252}Cf sources) was met by the design of the SM assemblies and was verified by the certification measurements.

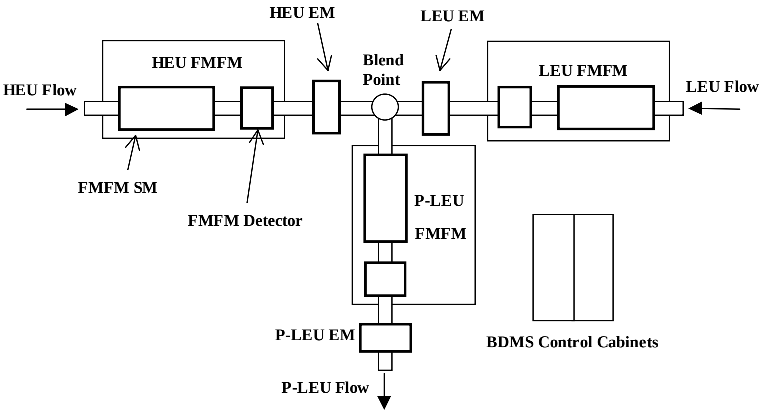

Fig. 11. Block diagram of the BDMS equipment installation on the HEU blending system at ECP.

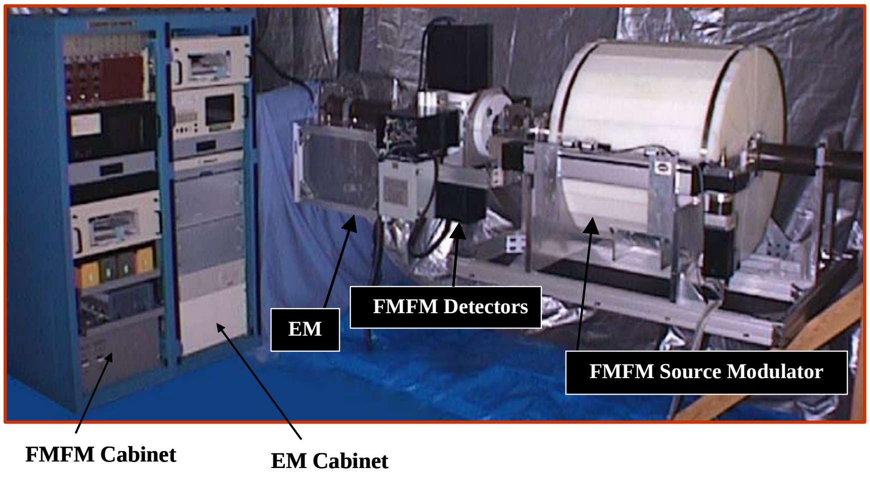

Fig. 12. The BDMS for the HEU blending tee leg.

Table 1. FMFM assembly dimensions and weights

Major assembly	Number of assemblies	Assembly dimensions, length × width × height (cm)	Weight per assembly (kg)
Control cabinet	1	58 × 80 × 190	175
Source modulator assembly	3	137 × 105 × 92	740
Detector assembly	3	58 × 91 × 91	194

4.1 FMFM ^{252}Cf NEUTRON SOURCES

The SM on each leg of the blending system uses a total of four neutron sources. Each source contains 3 μg of ^{252}Cf (half-life ~2.65 years). The sources provide total about 2.6×10^7 neutrons per second for the fission activation of the UF_6 gas flow under the SM. As shown in Fig. 2, the sources are installed in the SM in polyethylene source plugs; four source plugs are evenly distributed around the SM. The radial locations of the sources were determined from the Monte Carlo modeling studies for maximizing the thermal neutron flux under the SM [5]. The sources need to be replaced about every 2 years to maintain the performance of the FMFM.

4.2 UF_6 GAS PRESSURE

The recommended UF_6 gas pressure range for operation of the FMFM equipment is between 50 and 60 Torr (regulated) at the locations where the FMFM equipment is installed.

4.3 FMFM FLOW REGIME OPERATIONS AND UF_6 GAS VELOCITY

The FMFM can operate with either laminar or turbulent UF_6 gas flow. At ECP, the FMFM is designed to measure the laminar flow of the HEU leg and the turbulent flow of the LEU and P-LEU legs. Table 2 specifies the range of gas velocities that the FMFM can measure.

Table 2. UF_6 gas velocity ranges for FMFM operation

Flow regime	Flow velocity range (m/s)
Laminar	0.02 to 0.2
Turbulent	1.5 to 5.0

4.4 FMFM PERFORMANCE PARAMETERS

Table 3 shows the range of variables over which the FMFM is designed to operate, along with their measurement uncertainty.

Table 3. FMFM flow measurement range and associated uncertainty

Flow parameter	Measurement range	Uncertainty (%)
Gas velocity, m/s		
HEU leg	0.02 to 0.2	± 5
LEU leg	1 to 5	± 5
P-LEU leg	1 to 5	± 5
Fissile mass flow, g/s		
HEU leg	0.10 to 1.0	± 25
LEU leg	0.05 to 0.5	± 25
P-LEU leg	0.15 to 1.5	± 25

4.5 RECOMMENDED FMFM EQUIPMENT INSTALLATION CONFIGURATION AT ECP

This section describes the recommended installation configuration for all major FMFM components in the ECP facility. Figures 13 and 14 show the recommended installation configuration for the FMFM assemblies for the HEU, LEU, and P-LEU legs. The SM-to-detector separation distances, optimized for the process legs, are obtained from simulation modeling studies [2] to achieve the design performance (i.e., at a given shutter period and detector background, the time delay was optimized for the expected velocity range of measurements). The FMFM assemblies include the supplemental polyethylene neutron shielding, as shown in Figs. 13 and 14.

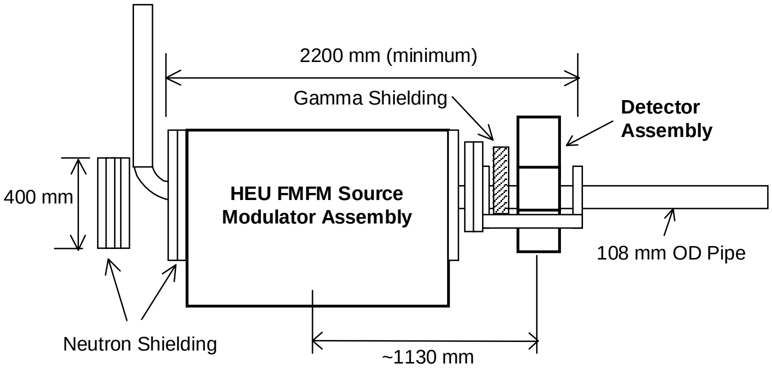

Fig. 13. Recommended FMFM installation configuration for HEU leg.

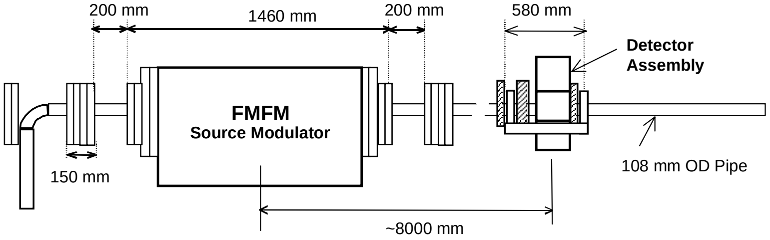

Fig. 14. Recommended FMFM installation configuration for the LEU and P-LEU legs.

The recommended FMFM system configuration provides lower cross talk (background), such as minimum back shine from the SM to detectors, among the HEU, LEU, and P-LEU process legs. Also, as shown in Fig. 15, supplemental gamma shielding may be installed to further lower the background signal resulting from the sources in the SM on the HEU, LEU, and P-LEU legs.

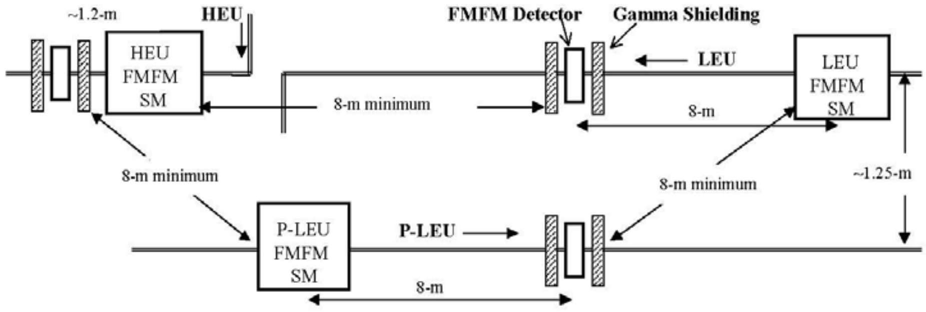

Fig. 15. Recommended FMFM installation configuration for all legs. The configuration is designed to reduce the cross talk between the sources in the SMs and the detectors.

5. BDMS IMPLEMENTATION STATUS

In December 2001, after more than a month of complete operational testing at ORNL, the BDMS system equipment was packed in 32 crates and was shipped to ECP. The joint U.S. and ECP inventory of the crates was performed in late February 2002, and the required 30-day security inspection by MINATOM was completed. In March 2002, a Russian delegation participated in a week of training held at ORNL on the installation and operation of the BDMS equipment (see Fig. 16). The following topics were included in the training:

- introduction to the BDMS operation and major components and their functionalities;
- familiarization with the BDMS software and its operation and practice;
- hands-on installation and practice with a detailed implementation work plan for ECP;
- the BDMS sources and their replacement procedures;
- maintenance activities;
- introduction to the BDMS manuals; and
- introduction to the blend point check form, BP-1 for data removal, its use and practice.

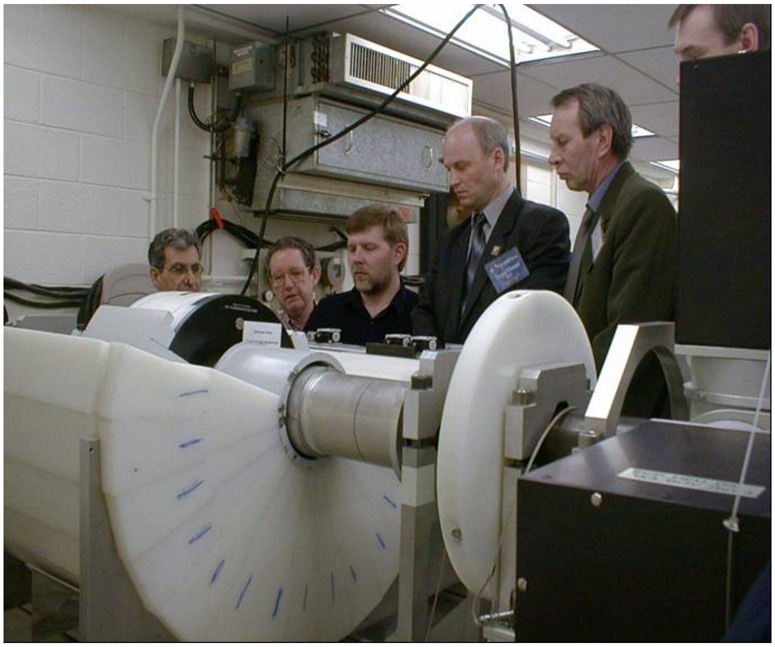

Fig. 16. The ECP BDMS training for the Russian delegation at ORNL, March 18–27, 2002.

The recommended installation schedule and work plan were prepared by DOE and were provided to MINATOM.

The BDMS implementation was accomplished at ECP in February 2003. The BDMS hardware was successfully installed, and the system was calibrated and accepted for operation by MINATOM to be used by the DOE HEU Transparency Implementation Plan. The main BDMS implementation activities in February 2003 were to

- perform background measurements on the evacuated piping,
- complete calibration of the system, and
- work with the Russian Certification Commission selected by MINATOM to verify that the system met its criteria and that that the system was placed into transparency operation, and
- confirm operation of the installed system.

All four objectives were successfully accomplished, and the Russian Commission approved the ECP BDMS for transparency operation.

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